# Airway Humidification During High-Frequency Percussive Ventilation

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**BACKGROUND: We were concerned about the risk of inadequate humidification during high-frequency percussive ventilation (HFPV). METHODS: We studied 5 humidifiers during HFPV with a lung model, at bias gas flows of 10 L/min, 30 L/min, and 50 L/min, and compared the results to those from a comparator ventilator/humidifier setup and to the minimum temperature (30°C) and humidity (30 g/L) recommended by the American Association for Respiratory Care, at both regular room temperature and a high ambient temperature. Temperature was measured at the humidifier outflow point and at the artificial carina. Humidity was measured at the artificial carina. RESULTS: Of the 7 HFPV/humidifier combinations, 2 (the MR850 at a bias flow of 50 L/min, and the ConchaTherm Hi-Flow with VDR nebulizer) provided a carinal temperature equivalent to the comparator setup at room temperature, whereas one HFPV/humidifier combination (the ConchaTherm Hi-Flow with modified programming, at bias flows of 30 L/min and 50 L/min) provided a higher carinal temperature. At high ambient temperature, all of the setups delivered lower carinal temperature than the comparator setup. Only 2 setups (the ConchaTherm with modified programming at a bias flow of 50 L/min, and the ConchaTherm Hi-Flow with VDR nebulizer) provided carinal humidification equivalent to the comparator setup, without regard to ambient temperature; the other humidifiers were less effective. The ConchaTherm with modified programming, and the ConchaTherm with the VDR nebulizer provided the most consistent humidification. CONCLUSION: HFPV's distinctive gas-flow mechanism may impair gas heating and humidification, so all humidification systems should be tested with HFPV prior to clinical use.** *Key words: high-frequency percussive ventilation, high-frequency ventilation, airway humidification.* [Respir Care 2009;54(3):350–358.]

## Introduction

In general, poor heating and humidification of inspired gases during mechanical ventilation is due to ineffective conditioning of cold anhydrous gas. Current-generation heated humidifiers can provide an absolute humidity range of 30–44 g/L and a gas temperature range of 30–41°C through the use of a water vaporization algorithm and a heated-wire circuit. Those humidity and temperature ranges have been deemed tolerable to the airway mucosa; they approximate normal human tracheobronchial conditions and comply with current American Association for Respiratory Care (AARC) recommendations for the minimum acceptable heating and humidification during mechanical ventilation ($> 30°C$, absolute humidity $> 30$ mg/L).[1-3]

Anecdotal experience at our burn center raised concern that inadequate humidification during high-frequency percussive ventilation (HFPV) was causing mucus plugging, loss of airway patency, and/or endotracheal tube (ETT) occlusion. Patients on HFPV can be vulnerable to inadequate humidification for 2 reasons. First, unlike most me-

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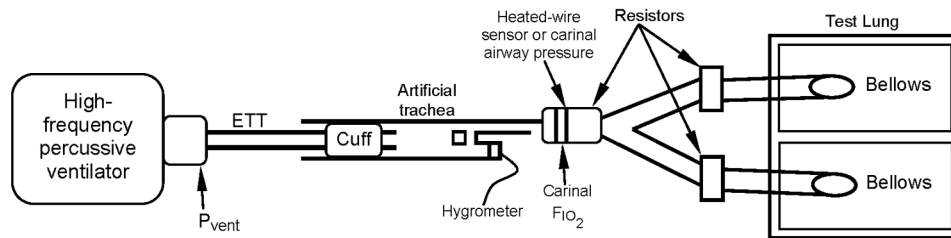Prescribed by ANSI Std Z39-18

Fig. 1. Schematic of test setup. ETT = endotracheal tube. $P_{vent}$ = proximal airway pressure. $F_{IO_2}$ = fraction of inspired oxygen.

Table 1. Humidifiers Studied

| Model | Manufacturer | Type |
|---|---|---|
| MR730 | Fisher-Paykel Healthcare, Auckland New Zealand | Heated pass-over |
| MR850 | Fisher-Paykel Healthcare, Auckland New Zealand | Heated pass-over |
| ConchaTherm Hi-Flow | Hudson RCI, Temecula, California | Heated wick |
| 2000i | Vapotherm, Stevensville, Maryland | Heated countercurrent membrane |
| Tracheobronchial jet nebulizer* | Percussionaire, Sandpoint, Idaho | Unheated continuous jet nebulization |

* This is the humidifier recommended by Percussionaire.

chanical ventilators, which direct the gas through a heated humidifier for delivery at the circuit Y-piece, in HFPV the gas goes directly to the circuit Y-piece, permitting most of the gas to bypass a humidifier before reaching the patient. Second, an HFPV-independent continuous (bias) gas flow must be used in which the gas passes via tubing to the humidifier, then to the circuit Y-piece. The resulting gas mixture may or may not have acceptable heat and humidity. We used a mechanical test lung with an artificial airway to model carinal heat and humidification during various HFPV settings and ambient room temperatures with the humidification systems in use at our regional burn center.

## Methods

### Ventilator, Airway, and Lung-Model Setup

The HFPV device (VDR-4, Percussionaire, Sandpoint, Idaho) combines a high-frequency percussive (pulsatile) waveform (100–900 cycles/min) with a lower-rate, conventional ("convective") time-cycled, pressure-limited breath (eg, conventional respiratory rates of 5–30 cycles/min).[4]

As in prior experiments,[4] the HFPV was interfaced with a mechanical test lung (5600i, Michigan Instruments, Grand Rapids, Michigan) via an artificial trachea intubated with an 8.0-mm inner-diameter cuffed ETT (Hi-Lo, Mallinckrodt, St Louis, Missouri) (Fig. 1). Test-lung compliance was set at 0.04 L/cm $H_2O$.

### Humidifier Setups and Programming

We studied 5 humidifiers (Table 1), 7 humidifier setups, 1 modified humidifier programming approach, and 1 humidifier/nebulizer combination. All 5 humidifiers are com-

monly used at the regional burn center at Brooke Army Medical Center, San Antonio, Texas.

HFPV requires a continuous gas flow ("bias flow") through the humidifier and then to the circuit Y-piece and the HFPV "phasitron" (the device that generates the high-frequency gas pulses). In our experiments the bias flow (at 10 L/min, 30 L/min, or 50 L/min) was administered via approximately 2 m of oxygen tubing from a wall oxygen outlet flow meter (Timeter, Allied Healthcare, St Louis, Missouri) to the humidifier, then to a small T-piece adapter at the distal end of the phasitron (the equivalent of the circuit Y-piece in a conventional ventilation circuit), and then to the test lung (Fig. 2). Thus, relatively cold, anhydrous gas entered the phasitron, then combined with humidified gas from the humidifier, which was delivered to the mechanical lung. We measured the flow with a flow sensor (VT Plus, BioTek Instruments, Winooski, Vermont) between the wall outlet and the humidifier.

Because of design limitations of the Vapotherm, we tested it only at bias flows of 10 L/min and 40 L/min (Fig. 3). The ConchaTherm Hi-Flow plus VDR nebulizer setup used nebulizer gas flow, discussed below.

Each MR730 and MR850 was attached to the phasitron via the manufacturer-specified heated-wire circuit. We studied the MR730 with the heated-wire circuit deactivated and activated, to test for differences in water-vapor delivery during ambient heating. The MR730 was set to its maximum temperature setting (39°C) throughout the experiments. The MR850 is auto-adjusting.

The ConchaTherm Hi-Flow and the jet nebulizer were individually connected to the phasitron via approximately 1 m of standard corrugated tubing, with a standard water trap. We also tested one humidifier combination: the VDR nebu-
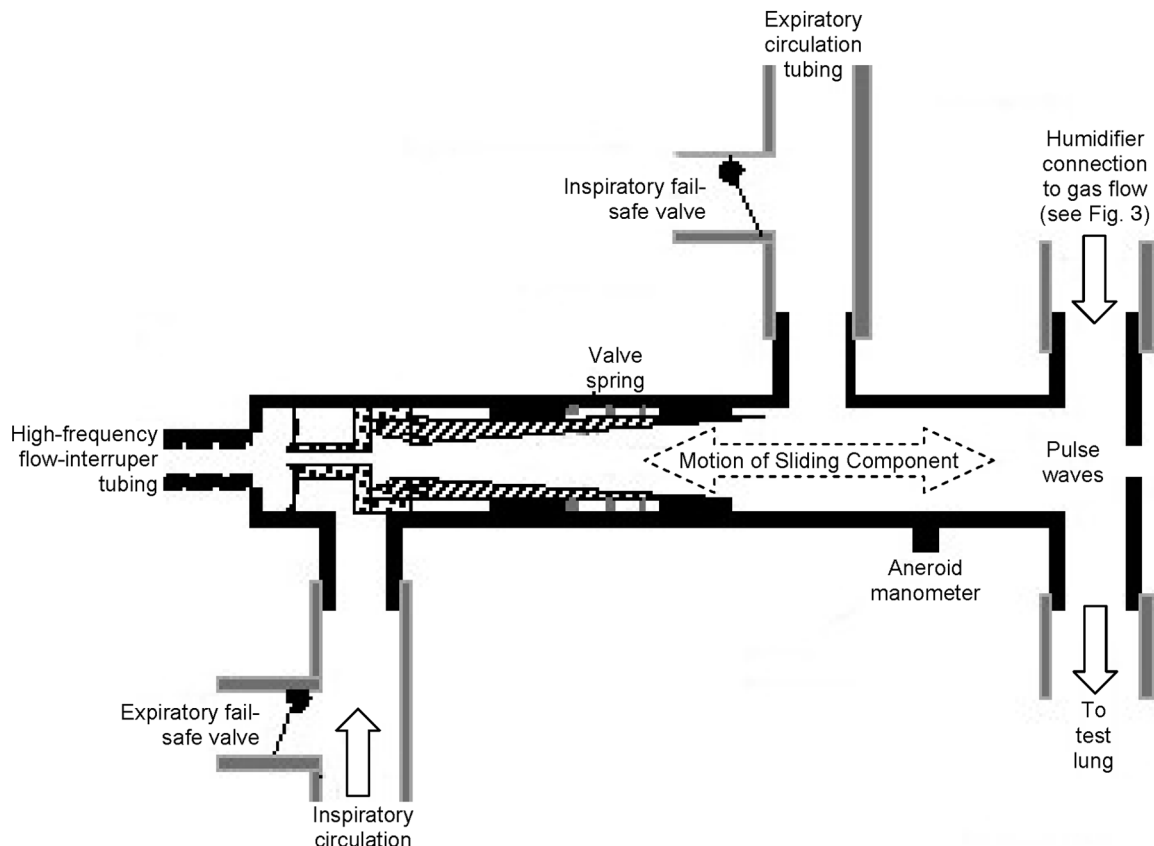
Fig. 2. Schematic of T-piece connection with the phasitron component of the high-frequency percussive ventilation device and connections to the humidifier and ventilation circuit components.

lizer with the ConchaTherm Hi-Flow (Fig. 4). Essentially the VDR is a jet nebulizer with a gas flow of $16 \pm 2$ L/min diverted from the VDR blender. Prior to each experiment the VDR nebulizer gas flow was measured with the VT Plus flow sensor. The VDR nebulizer was connected with approximately 15 cm of corrugated tubing to the ConchaTherm Hi-Flow, which was then connected with approximately 1 m of corrugated tubing to the HFPV inspiratory circuit.

The ConchaTherm Hi-Flow has 2 adjustable variables: flow can be set at high or low, and temperature, the dial for which has an arbitrary 1–11 scale. Both of those settings can be programmed based on ventilator peak flow. Peak flow is not measured during HFPV, so we set the humidifier based on the administered bias flow. We also studied the ConchaTherm at a modified setting with a fixed high temperature (11 on the 1–11 scale) while adjusting the high-flow and low-flow setting, per the user manual. The manufacturer of the ConchaTherm calls the latter setup modified programming.

The Vapotherm has integral tubing, which we attached to the phasitron with an adapter.

## Ventilator Programming

Each humidifier was tested in triplicate at convective settings of inspiratory time 2 s, expiratory time 2 s, mean airway pressure 20 cm $H_2O$, and zero positive end-expiratory airway pressure. To examine the effects of changing the HFPV gas-flow times (ie, inspiratory intervals), each humidifier was studied with single trials at multiple HPFV settings. Settings included convective inspiratory times of 1 s, 2 s, and 3 s, with a conventional respiratory rate of 15 breaths/min. The HFPV frequency was set at either 300 cycles/min or 600 cycles/min, and a high-frequency inspiratory-expiratory (I-E) ratio of 1:3.

HFPV pulsatile flow was set to attain the desired proximal airway pressure ($P_{vent}$, measured by an integral aneroid manometer in the HFPV circuitry) and adjusted to sustain the same pressure throughout each experiment. Because the 300 cycles/min and 600 cycles/min frequencies at normal I:E of 1 s:3 s or 2 s:2 s could not sustain $P_{vent}$ above 30 cm $H_2O$, we tested the 300 cycles/min setting only at 30 cm $H_2O$ and a convective I:E of 3 s:1 s.

Each humidifier also underwent one trial with concurrent application of oscillatory continuous positive airway pressure (CPAP) and demand CPAP, both of which were set at 5 cm $H_2O$, which resulted in a total positive end-expiratory pressure of 10 cm $H_2O$. The HFPV settings for that trial were 300 cycles/min, $P_{vent}$ 20 cm $H_2O$, and convective I:E 2 s:2 s.
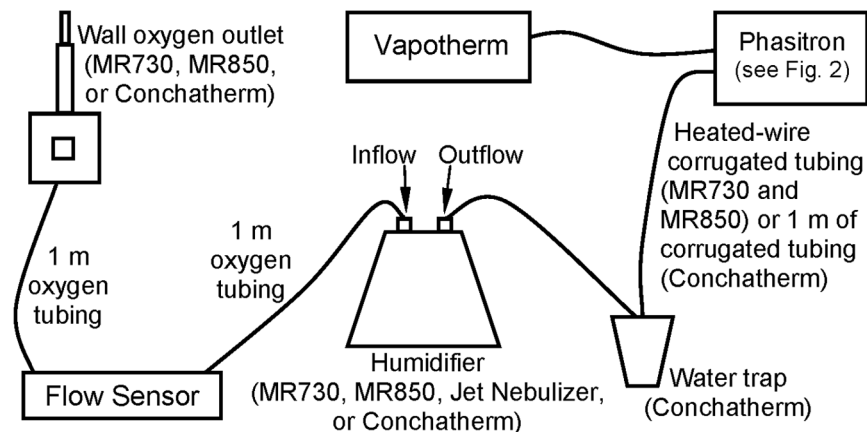
Fig. 3. Schematic of the test setup with the MR730, MR850, jet nebulizer, and ConchaTherm Hi-Flow.

## Measurements

Airway humidity and airway temperature were measured at the artificial carina with a calibrated hygrometer (Hygrotec MR Plus 2350 with MDR-3 humidity probe, General Electric Healthcare, Waukesha, Wisconsin), which has a relative humidity accuracy of $\pm 2\%$ in the range 0–90%, $\pm 3\%$ in the range 90–100%, temperature accuracy of $\pm 0.5°C$, and precision of $> 0.5\%$ of the relative humidity. The MDR-3 capacitance humidity probe is made of a silicon-based polymer and has a sintered hydrophobic stainless steel filter (that allows penetration of water vapor but not water droplets) and a platinum-based temperature sensor. We used a second temperature probe (Traceable, Friendswood, Texas) throughout the experiments to verify the temperature measurements. Interchanging the 2 hygrometer probes showed a $\pm 5\%$ agreement in the temperature measurements.

We did not measure the outflow temperature of the Vapotherm because its circuit attaches directly to the phasitron. We recorded the VapoTherm's own integral thermometer reading as the VapoTherm's outflow temperature. All the sensors but the Traceable probe were placed in-line at the artificial carina (distal to the tip of the ETT) via an airtight side-sampling port that added approximately 35 mL of dead space. The hygrometer's measuring tip was 10 cm from the tip of the ETT.

Prior to each trial we measured the ambient and artificial carina air temperature and absolute humidity. With the exception of the 30-min "single trials" of different ventilator programming scenarios, each humidifier was tested at the same ventilator settings in 3 separate 60-min trials. Data were collected in the last minute of each trial and tabulated to provide a mean $\pm 1$ standard deviation result. Between each trial the ventilator circuit and test lung were flushed for 30 min with dry compressed air, and we visually confirmed the absence of condensation in the transparent tubing and mechanical lung. Randomly conducted longer (2-h) humidification trials found similar results and did not cause water pooling in the test lung. Each humid-
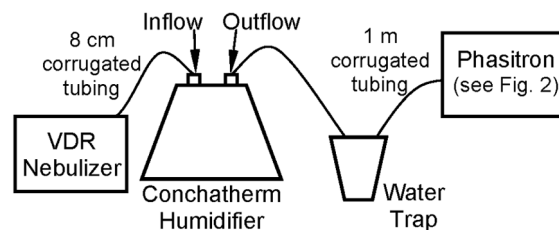


Fig. 4. Schematic of the test setup with the ConchaTherm Hi-Flow humidifier and VDR nebulizer.

ifier was tested at normal (22–24°C) and high (32–34°C) ambient temperatures in a typical burn care unit.

## Comparator Setup

After the HFPV/humidifier experiments we tested a comparator humidifier/ventilator setup that combined the ConchaTherm with a high-frequency oscillatory ventilator (3100B, SensorMedics, Yorba Linda, California). The 3100B directs all of the applied gas through the humidifier. We programmed the 3100B to a frequency of 600 cycles/min, mean airway pressure 20 cm $H_2O$, power setting 60 cm $H_2O$, and bias flow 50 L/min. We set the ConchaTherm humidifier to the manufacturer's specifications.

## Statistical Analysis

We made 3 sets of measurements with each ventilator/humidifier/flow setup, at a single HFPV setting, so our experiment was able to detect a 4.8-standard-deviation effect size. With an effect size that large the study is underpowered to draw a statistical comparison between the comparator setup and HFPV, so we did not use inferential statistics. We performed a linear regression analysis to determine the relationship between bias flow, humidifier outflow temperature, carinal humidity, and carinal temperature, at room and ambient heating temperatures. Each ventilator/humidifier/flow combination was also compared against the AARC-recommended minimum temperature and humidity values ($> 30°C$, absolute humidity $> 30$ g/L).[2]

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Table 2. Humidifier Outflow Temperature and Carinal Humidity and Temperature

| Temperature and Humidity Measurement Location and Test Conditions | Bias Flow Setting (L/min) | Humidifier Setup | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | MR 730 | MR 850 | Jet Nebulizer | Vapotherm | ConchaTherm Hi-Flow (manufacturer's algorithm) | ConchaTherm Hi-Flow (modified programming) | ConchaTherm Hi-Flow Plus Nebulizer at Temperature Settings of 7, 9, and 11 |
| Humidifier outflow temperature (mean ± SD °C) | 10 | 39.1 ± 1.1 | 36.2 ± 0.4 | 13.6 ± 0.5 | 37.0 ± 0.0 | 46.5 ± 0.6 | 56.1 ± 1.7 | 36.4 ± 1.3 |
| | 30 | 40.3 ± 0.2 | 36.1 ± 0.1 | 12.3 ± 0.0 | 37.0 ± 0.0* | 42.5 ± 1.0 | 44.9 ± 1.1 | 40.8 ± 1.0 |
| | 50 | 39.3 ± 0.5 | 36.8 ± 0.5 | 12.1 ± 0.2 | ND* | 37.7 ± 0.3 | 43.6 ± 1.4 | 43.5 ± 1.8 |
| Carinal absolute humidity (mean ± SD g/L) | 10 | 18.0 ± 1.5 | 16.2 ± 0.2 | 12.3 ± 0.2 | 15.8 ± 0.4 | 11.2 ± 0.4 | 13.2 ± 0.6 | 26.1 ± 0.7 |
| | 30 | 24.3 ± 1.3 | 23.5 ± 0.6 | 12.0 ± 0.1 | 24.9 ± 0.3* | 20.3 ± 0.4 | 29.5 ± 1.4 | 30.1 ± 1.7† |
| | 50 | 29.6 ± 0.5 | 28.2 ± 0.6 | 11.4 ± 0.2 | ND* | 22.7 ± 0.1 | 33.0 ± 4.3† | 32.7 ± 2.7† |
| Carinal temperature (mean ± SD °C) | 10 | 23.9 ± 0.2 | 25.1 ± 0.1 | 16.4 ± 0.3 | 22.8 ± 0.6 | 22.5 ± 1.1 | 27.0 ± 1.8 | 28.0 ± 1.4 |
| | 30 | 26.9 ± 0.2 | 27.6 ± 0.7 | 16.3 ± 0.3 | 26.5 ± 0.1* | 24.2 ± 0.9 | 32.0 ± 2.8† | 29.6 ± 2.4 |
| | 50 | 29.2 ± 0.1 | 29.5 ± 0.7 | 16.3 ± 0.2 | ND* | 25.2 ± 0.3 | 33.7 ± 0.6† | 31.6 ± 1.7† |
| Ambient heating; humidifier outflow temperature (mean ± SD °C) | 10 | 38.2 ± 0.1 | 36.5 ± 0.0 | 16.7 ± 0.4 | 37.0 ± 0.0 | 41.9 ± 0.9 | 55.0 ± 1.2 | 37.7 ± 0.3 |
| | 30 | 39.9 ± 0.4 | 36.4 ± 0.5 | 16.5 ± 0.4 | 37.0 ± 0.0* | 39.3 ± 0.9 | 42.5 ± 0.7 | 41.5 ± 1.4 |
| | 50 | 38.6 ± 0.4 | 37.0 ± 0.2 | 15.4 ± 0.1 | ND* | 35.8 ± 1.0 | 43.4 ± 0.5 | 45.2 ± 1.3 |
| Ambient heating; carinal absolute humidity (mean ± SD g/L) | 10 | 12.1 ± 0.5 | 10.7 ± 1.2 | 17.1 ± 0.1 | 16.8 ± 0.3 | 14.0 ± 1.5 | 22.4 ± 1.6 | 28.9 ± 2.8 |
| | 30 | 15.5 ± 0.6 | 14.2 ± 0.2 | 14.2 ± 0.1 | 23.9 ± 1.1* | 21.5 ± 0.6 | 28.0 ± 2.5 | 34.6 ± 2.6† |
| | 50 | 18.4 ± 0.2 | 18.4 ± 0.2 | 12.4 ± 0.1 | ND* | 25.4 ± 2.1 | 36.8 ± 2.7† | 41.3 ± 1.5† |
| Ambient heating; carinal temperature (mean ± SD °C) | 10 | 33.7 ± 1.1† | 33.7 ± 0.6† | 26.3 ± 0.5 | 32.6 ± 1.4† | 33.0 ± 0.3† | 33.4 ± 0.2† | 34.4 ± 0.7† |
| | 30 | 32.7 ± 0.7† | 34.8 ± 0.3† | 25.8 ± 0.4 | 34.4 ± 0.6*† | 33.1 ± 1.0† | 33.6 ± 0.4† | 34.8 ± 0.7† |
| | 50 | 34.4 ± 0.0† | 35.9 ± 0.3† | 22.6 ± 0.5 | ND* | 33.8 ± 0.3† | 35.0 ± 0.2† | 36.2 ± 0.1† |

* Bias flow 40 L/min. ND = no data for bias flow of 50 L/min, because the VapoTherm could not be tested at that flow.
† Meets minimum temperature and humidity recommended by the American Association for Respiratory Care.

## Results

Ambient temperature and absolute humidity with and without ambient heating were 22.5 ± 1.5°C and 10.2 ± 1.1 mg/L versus 33.0 ± 1.1°C and 10.7 ±0.8 g/L, respectively. To obtain a baseline reading, we measured during HFPV without a humidifier, and the room temperature carinal values were 22.2 ± 0.4°C and 2.6 ± 1.0 mg/L, whereas with ambient heating they were 32.4 ± 0.3°C and 3.9 ± 1.0 mg/L. The comparator setup results were 31.6 ± 0.2°C and 35.0 ± 0.2 mg/L at room temperature, and 39.1 ± 0.6°C and 45.1 ± 1.8 mg/L with ambient heating.

The 2 pass-over heated humidifiers (MR730 and MR850) had similar results, which will be discussed in tandem. At normal ambient temperature, neither the MR730 nor the MR850, regardless of the bias flow, sustained adequate carinal temperature or humidity relative to the recommended 30°C, nor did they attain the heat and humidity achieved by the comparator setup (Table 2). High ambient temperature resulted in carinal temperature above the recommended 30°C with both the MR730 and MR850, but the increase in carinal temperature did not affect carinal absolute humidity. The MR850 delivered lower absolute humidity with ambient heating. During ambient heating the MR730 with the activated heated-wire circuit sensor also had lower carinal absolute humidity, which significantly improved when the heated-wire sensor was turned off (Fig. 5). The various convective I-E ratios, frequency settings, and oscillatory demand CPAP did not significantly modulate the carinal humidity content or temperature (Figs. 6 and 7).

The HFPV jet nebulizer reduced the carinal temperature and absolute humidity, irrespective of ambient conditions and relative to the recommended 30°C and 30 g/L and the comparator setup (see Table 2). The gas temperature and humidity from the nebulizer device was lower relative to ambient. Bias flows and HFPV settings did not influence carinal gas treatment (see Table 2). Ambient heating improved carinal temperature but not absolute humidity.

The Vapotherm failed to attain the recommended 30°C and 30 g/L (see Table 2). Increasing the bias flow improved the carinal humidity and temperature, but HFPV settings and ambient heating did not raise the carinal temperature and humidity to the control levels. Ambient heating did, however, increase carinal temperature.

The ConchaTherm set per the manufacturer's algorithm failed to provide the recommended 30°C and 30 g/L at room temperature (see Table 2). The convective, high-frequency, and CPAP settings did not alter the humidity (Figs. 8 and 9). During ambient heating the ConchaTherm's
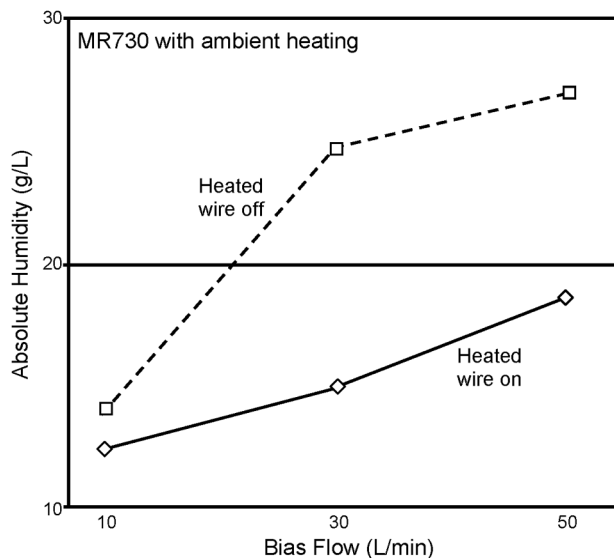
Fig. 5. Absolute humidity at the carina versus bias flow with the MR730 humidifier at heated ambient conditions, with activated and inactivated auto-adjusting heated wire.

carinal temperature and humidity values exceeded the recommended 30°C and 30 g/L, but were less than those of the comparator setup. When the bias flow was increased from 30 L/min to 50 L/min, using the manufacturer's algorithm, the flow setting is changed (from low-flow to high-flow) but the temperature dial is reset from 9 to 7, which reduces the heating of the wick and decreases the delivered humidity and outflow temperature.

Setting the ConchaTherm temperature dial to its fixed maximum (11, with the modified programming) while adjusting only the bias flow setting to the manufacturer's recommended setting increased both the carinal temperature and the humidity (see Table 2). The carinal temperature with the ConchaTherm with the modified programming at 30 L/min and 50 L/min was higher than that of the comparator setup at room temperature but less than the comparator setup with ambient heating. The humidity with the modified algorithm at 50 L/min was similar to the comparator setup. However, both the carinal temperature and humidity, irrespective of ambient conditions, were higher than the recommended 30°C and 30 g/L only at 50 L/min. Changing the HFPV inspiratory and expiratory settings did not significantly modulate the carinal readings (data not shown).

The ConchaTherm at the maximum temperature setting, in conjunction with the gas flow from the nebulizer, provided carinal temperature and humidity levels above the recommended 30°C and 30 g/L. The Conchatherm/nebulizer arrangement also implemented carinal humidity and temperature values similar to those of the comparator setup (see Table 2). As with the other setups, the convective, high-frequency, and CPAP settings did not significantly affect carinal temperature or absolute humidity (data not shown).

We performed additional experiments with no water in the nebulizer, so anhydrous gas drove the water vapor generated by the heated-wick device into the mechanical lung setup, and there was no difference in carinal absolute humidity or carinal temperature with or without water in the nebulizer (data not shown).

Linear regression analysis showed a significant correlation between humidifier outflow temperature and carinal temperature and absolute humidity, irrespective of ambient conditions (Figs. 10 and 11). However, there was only a weak correlation between outflow temperature and carinal humidity at room temperature ($r^2 = 0.181$, $n = 60$, $P < .001$) and ambient heating ($r^2 = 0.206$, $n = 60$, $P < .001$) conditions. There was no significant correlation between bias flow and carinal temperature, irrespective of room temperature. There was a weak correlation between bias flow and carinal humidity ($r^2 = 0.092$, $P = .019$) at room temperature, but not heated ambient conditions.

## Discussion

To our knowledge, this is the first study that has systematically evaluated multiple humidifier setups during HFPV. We compared commonly used HFPV/humidifier combinations to a comparator setup and to the AARC's recommended minimum humidity (30 g/L) and temperature (30°C).[2] Our comparator HFPV/humidifier setup passes all of the air flow through the humidifier, which allowed us to study the "bypass effect" of the HFPV circuit design.

We found one curious deficiency in the ability of any of the HFPV/humidifier setups to approximate the comparator setup during high ambient temperature. The simple bypass effect allowed for a persistent disproportionate mixing of larger amounts of cool gas with bias flow delivered humidified air, reducing the carinal temperature. The bypass effect was made more obvious (relative to the comparator setup) against a warm ambient background. In contrast, the comparator HFPV/humidifier apparatus avoided the bypass effect and exploited ambient conditions to improve carinal humidity and temperature.

The AARC-recommended heat and humidity were most consistently achieved by the ConchaTherm wick-based humidifier. It is perhaps the large surface area, flow adaptability, and heating capacity of the ConchaTherm that made it more capable of functioning in challenging environments.

Bias flow exerted a limited effect; at room temperature it marginally correlated with carinal humidity and temperature. In general, as long as the humidifier can increase its water-vapor generation to match the bias flow, more water vapor will be delivered to the carina. This increase in water-vapor capacity can only occur if the bulk of the gas that is conditioned by the humidifier is delivered to the ETT. We previously found that a bias flow administered at either the circuit Y-piece (eg, connecting point of the MR730, MR850, ConchaTherm Hi-Flow, jet nebulizer, and the Vapotherm) or the
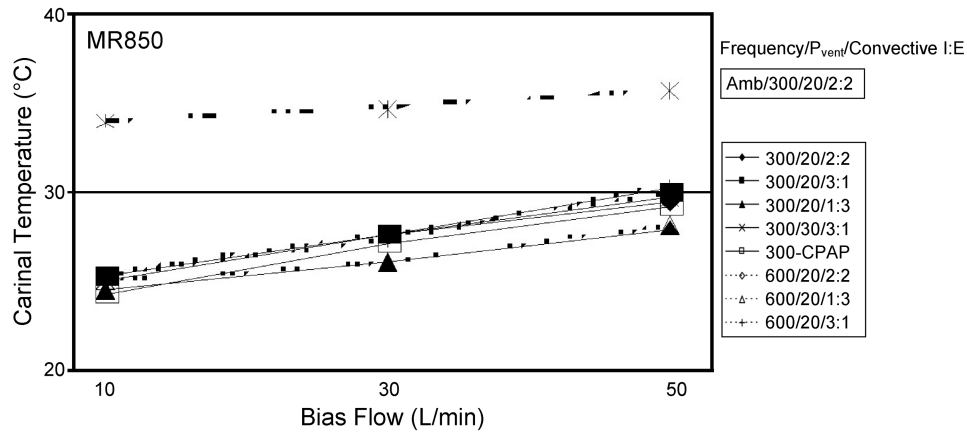
Fig. 6. Temperature at the carina versus bias flow with the MR850 humidifier, at frequency of 300 or 600 cycles/min, proximal airway pressure ($P_{vent}$) of 20 or 30 cm $H_2O$, and convective inspiratory-expiratory ratio of 2:2, 3:1, or 1:3 seconds. CPAP = continuous positive airway pressure. Amb = ambient heating.
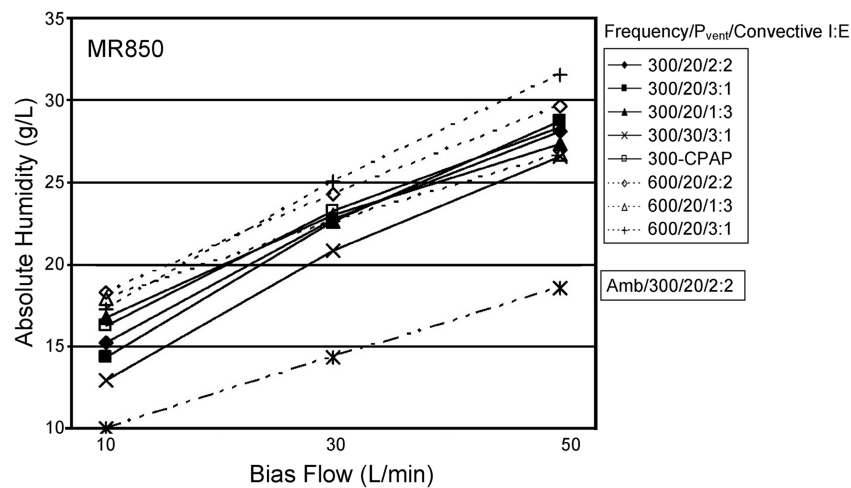


Fig. 7. Absolute humidity at the carina versus bias flow with the MR850 humidifier, at frequency of 300 or 600 cycles/min, proximal airway pressure ($P_{vent}$) of 20 or 30 cm $H_2O$, and convective inspiratory-expiratory ratio of 2:2, 3:1, or 1:3 seconds. CPAP = continuous positive airway pressure. Amb = ambient heating.
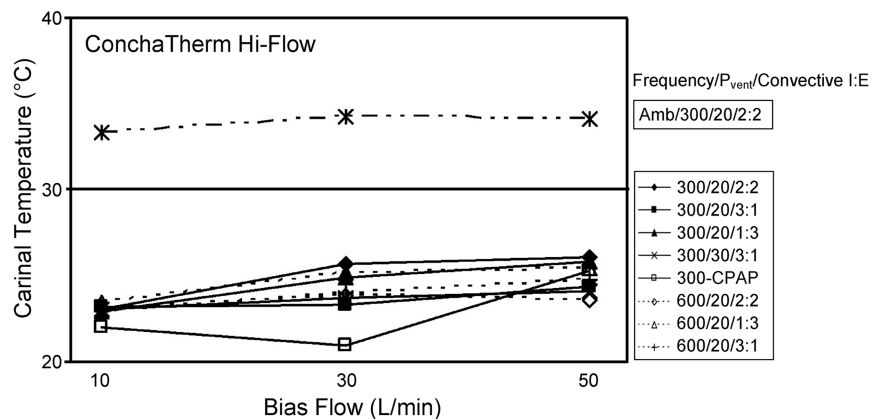


Fig. 8. Temperature at the carina versus bias flow with the ConchaTherm Hi-Flow humidifier, at frequency of 300 or 600 cycles/min, proximal airway pressure ($P_{vent}$) of 20 or 30 cm $H_2O$, and convective inspiratory-expiratory ratio of 2:2, 3:1, or 1:3 seconds. CPAP = continuous positive airway pressure. Amb = ambient heating.
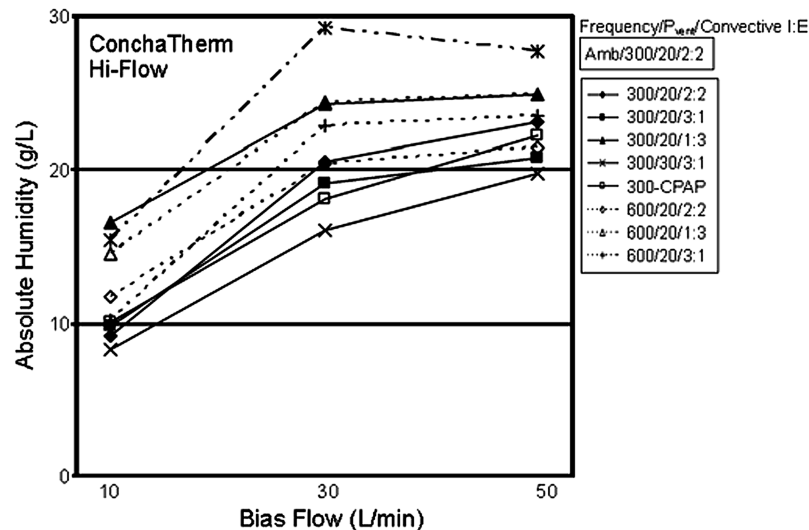
Fig. 9. Absolute humidity at the carina versus bias flow with the ConchaTherm Hi-Flow humidifier, at frequency of 300 or 600 cycles/min, proximal airway pressure ($P_{vent}$) of 20 or 30 cm $H_2O$, and convective inspiratory-expiratory ratio of 2:2, 3:1, or 1:3 seconds. CPAP = continuous positive airway pressure. Amb = ambient heating.
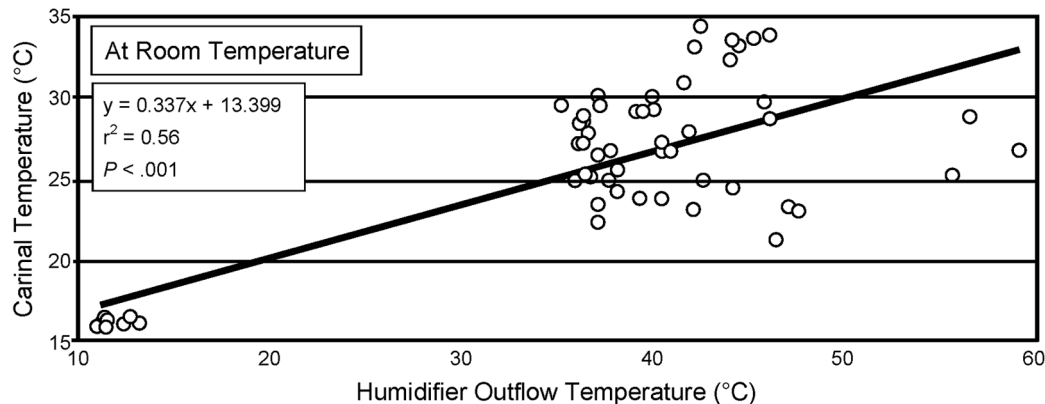


Fig. 10. Carinal temperature versus outflow temperature at room temperature.

inspiratory circulation tubing (eg, connecting point for the ConchaTherm Hi-Flow plus VDR nebulizer) can escape through 2 separate expiratory failsafe flap valves in the inspiratory and expiratory circuits.[4] We were unable to quantify the extent of redirected flow and therefore could not pinpoint flow redirection or the simple effect of HFPV flow bypassing as the predominant causes for that deficit.

The performance of the jet nebulizer served as a stark contrast to the heated humidifiers. The jet nebulizer has a fixed water-vapor-generation capacity, which was either unaffected or reduced by the applied bias flow. In addition to fixed vapor production, the cold gas temperature created by the compressed gas jet inherently limits the water-vapor carrying capacity of the gas. Our results suggest avoiding the use of the jet nebulizer alone as the sole humidification mechanism.

High ambient temperature increased the carinal temperature with all the setups, but decreased the carinal humidity with the MR850 and MR730 when the temperature

probe was activated. Lellouche et al found that auto-adjusting devices, in response to warm ambient air, may paradoxically decrease the heat administered to the pot, which severely reduces the water-vapor production.[5] As a corollary, with the MR730, turning off the heated-wire sensor substantially improved the carinal humidity and temperature. Although it may initially appear an intuitive and welcome means of preventing condensation (and attendant circuit obstruction) in the ventilator tubing, the heated-wire design is a poor surrogate for humidification in a heated room. Probably because of its lack of an external temperature probe, the ConchaTherm appeared to be unaffected by ambient conditions.

There are several findings of clinical concern. With a few exceptions, high bias flow implemented in conjunction with a heated humidifier provided heat and humidity at the lower limits of the acceptable ranges, so a burn patient cared for at a normal room temperature may receive inadequate humidification during HFPV. Perhaps even more
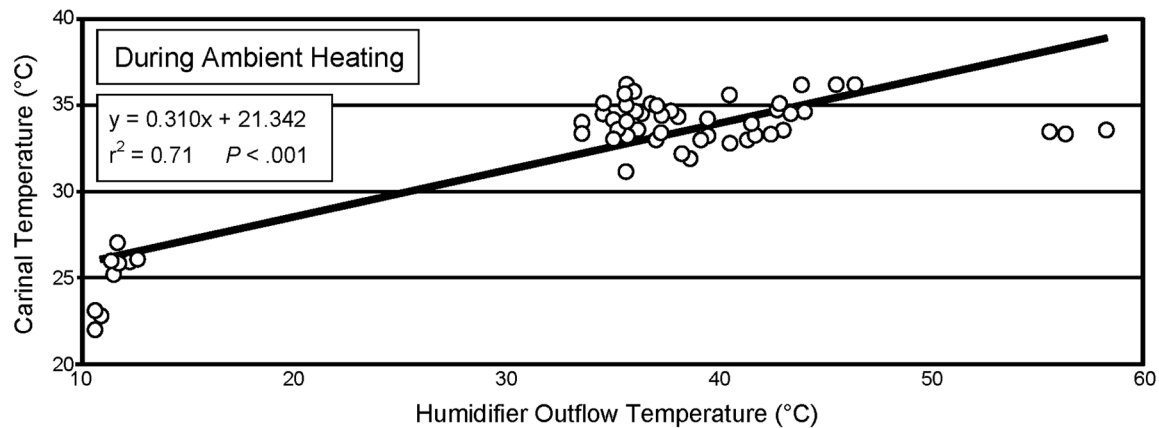
Fig. 11. Carinal temperature versus humidifier outflow temperature during ambient heating.

concerning is that the jet-nebulizer humidifier might create potentially injurious cold gas with grossly insufficient humidity. Care must also be exercised when using auto-adjusting humidifiers in warm environments. Reassuringly, despite the concerns about HFPV/humidifier interaction, humidifier outflow temperature significantly correlated with carinal temperature and humidity, which suggests that proximal sensors are suitable for carinal humidity and temperature monitoring during HFPV. We could not measure humidity at the humidifier outflow, because hygrometer supersaturation confounded the readings.

The present results may have limited application in the clinical setting. Our model lacked the heating and humidification capacity of the human airway and thus was an incomplete replica of clinical circumstances, but the high ambient temperature we tested represents a possible surrogate for body temperature in HFPV/humidifier modeling. However, our ambient heating approach affected the entire apparatus (humidifier, ventilator, and test lung), as opposed to simple airway heating, and thus still may not accurately model clinical circumstances. Although airway water-vapor generation was not modeled, the gas temperature and humidity at the carina and mainstem bronchus are assumed to be largely dependent on the temperature and humidity of the administered gas, not on the airway tissue. Despite the limits imposed by our artificial-airway-and-test-lung setup, we believe our methods gave a reproducible and clinically relevant model to explore the interaction of HFPV with various humidifiers.

Our findings are not intended to support one ventilator over another, but to use the comparator setup as a backdrop to understand how the unique attributes of the HFPVs design affect distal gas composition. By selecting the ConchaTherm as the comparison device, based on its consistent functioning with the HFPV, we introduced a potential bias against the other humidifiers. Despite the limitations, all of the HFPV/humidifier combinations appeared to deliver lower carinal temperatures during high ambient temperature, which illustrates the potential importance of the bypass effect.

The present study calls to attention the lack of observational data and interventional studies regarding the optimal range of airway temperature and humidity conducive to restoring inhalation-injury mucosa. Until such studies are completed, the reasonable course appears to be to provide heat and humidity that is considered safe and non-injurious to normal airway mucosa. Unfortunately, if "normalization" of airway humidity and temperature is required, then there appear to be few effective humidification systems for HFPV. As long as HFPV is used in burn care centers, exploration of alternative means of humidifying HFPV gas remains an imperative. Our investigation underscores the importance of heated humidifier validation testing with HFPV prior to clinical use.

## Conclusions

Of the studied humidifiers, only the ConchaTherm Hi-Flow (with or without modified programming, or in conjunction with the nebulizer) appeared to be capable of achieving the minimally acceptable temperature and humidity that were statistically no different from the comparator setup. Further investigation into means of improving heated water vapor delivery during HFPV in patients with inhalational injury is essential.

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